Quantum Electronics **45** (7) 604–606 (2015)

PACS numbers: 42.55.Px; 78.66.–w
DOI: 10.1070/QE2015v045n07ABEH015782

Study of the absorption coefficient in layers of a semiconductor laser heterostructure

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Abstract. **A method of studying the absorption coefficient in layers of semiconductor lasers is proposed. Using lasers based on MOVPE-grown separate-confinement heterostructures with a broadened waveguide, the absorption coefficient is investigated under pulsed current pumping. It is found that when the pump current flows through the laser in question, an additional internal optical absorption arises in the heterostructure layers. It is shown that an increase in the pump current density up to 20 kA cm^{-2} leads to an increase in absorption up to 2.5 cm^{-1}. The feasibility of studying free-carrier absorption in the active region is demonstrated.**

Keywords: *absorption coefficient, semiconductor laser, internal optical loss, pulsed pumping.*

1. Introduction

In this paper we continue to study the process of saturation of light–current (L–I) characteristics of high-power semiconductor lasers based on MOVPE-grown quantum separate-confinement double heterostructures with a broadened waveguide in a system of AlGaAs/GaAs/InGaAs solid solutions. Despite the large number of works on the subject, the reasons for the L–I characteristic saturation of semiconductor lasers at high pulsed pump currents still remain unexplained [1–7]. In our previous papers, an increase in internal optical loss with increasing pump current [1, 2] and a decrease in the rate of carrier capture into the active region with increasing concentration of charge carriers in this region [4, 8, 9] have been considered to be the main reasons for the saturation of L–I characteristics of semiconductor lasers.

The aim of this work is to develop a method for measuring the absorption coefficient in the cavity of a semiconductor laser and to study it at high levels of pulsed pump current.

2. Method for measuring the absorption coefficient

In [1, 2], we were able to experimentally demonstrate the dependence of the internal optical loss in a semiconductor laser on the current pump density. The most likely reason for the growth of the internal optical loss may be an increase in the free-carrier absorption in the waveguide layers at pulsed pumping [7, 10]. Therefore, a technique has been proposed to study the absorption coefficient in an operating semiconductor laser using probe radiation from another laser. The probe laser should emit a longer-wavelength radiation, so as not to experience self-absorption and not to be amplified in the material of the active region. At the same time, propagating through the waveguide, radiation of the probe laser will experience absorption by free charge carriers, comparable with radiation absorption of the laser in question.

In the waveguide of the laser under study, probe radiation is absorbed in accordance with Bouguer–Lambert–Beer law, and its intensity I at the output mirror of the cavity is defined by the formula

$$I = I_0 \exp(-\alpha_i L), \qquad (1)$$

where I_0 is the intensity of probe radiation coupled into the waveguide; α_i is the absorption coefficient in the laser heterostructure layers; and L is the length of its cavity.

A variation in the absorption coefficient will result accordingly in a change in the amplitude of probe radiation transmitted through the sample; therefore, recording this change, it is possible to calculate the absorption coefficient.

The scheme of the experimental setup is shown in Fig. 1. CW radiation of the probe laser (*1*) is coupled into the waveguide of the laser under study (*2*) through an AR-coated cavity mirror using an optical system of aspherical lenses. An optical isolator (*3*) eliminates the mutual influence of the laser in question and the probe one. Probe radiation emitted through the opposite cavity mirror of the laser under study is collected by the objective together with the radiation of the test sample and is directed to a beam splitter (*4*). Part of collected light is directed to a two-dimensional CCD-matrix (*5*) that allows one to control the quality of the probe radiation input. The main optical radiation flux of the test sample and probe radiation is sent to a monochromator (*6*), which is used as a filter that transmits only radiation of the probe laser. Then, the probe radiation is fed to a high-speed photodetector (*7*) and the signal is recorded by an oscilloscope (*8*). In the absence of a pulse of the injection current through the sample the oscilloscope detects a continuous signal of the probe laser.

When applying a pump current pulse to the laser in question, absorption by free carriers in its layers increases and, consequently, the amplitude of the probe radiation at the output from the laser decreases. On a continuous photoresponse signal the oscilloscope records a dip, the shape

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Received 11 February 2015
Kvantovaya Elektronika **45** (7) 604–606 (2015)
Translated by I.A. Ulitkin

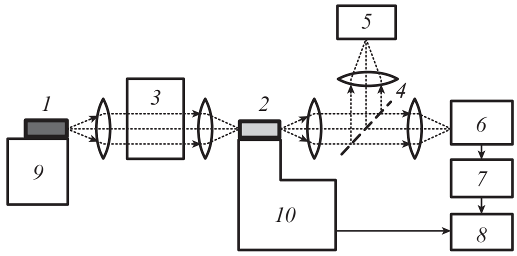

Figure 1. Scheme of the experimental setup:
(*1*) probe laser (λ = 1100 nm); (*2*) laser in question (λ = 1030 nm); (*3*) optical isolator; (*4*) beam splitter; (*5*) CCD-camera; (*6*) monochromator tuned to the transmission of radiation with λ = 1100 nm; (*7*) high-speed photodetector; (*8*) oscilloscope; (*9*) pumping and temperature control unit of the laser operating in cw mode; (*10*) pulsed pumping and temperature control unit.

and duration of which corresponds to the pump current pulse.

Unfortunately, this technique makes it impossible to measure the absolute value of the absorption coefficient in a laser waveguide, because we cannot determine with reasonable accuracy the absolute value of the probe radiation coupled into the waveguide of the laser; however, this method allows one to calculate its change due to the pump current flow through the laser under study, according to the formula:

$$\Delta\alpha_{\rm i} = \frac{1}{L}\ln\left(\frac{I_{\rm cw}}{I}\right), \qquad (2)$$

where $\Delta\alpha_{\rm i}$ is the change in the absorption coefficient; $I_{\rm cw}$ is the intensity of cw probe radiation in the absence of a current through the laser in question; and I is the probe radiation intensity in the case of current pumping through the laser under study.

3. Objects of research

We studied lasers based on broadened-waveguide quantum separate-confinement double heterostructures grown in AlGaAs/GaAs/InGaAs solid solutions, whose parameters are given in [1]. Using a standard procedure we fabricated lasers with a stripe contact width of 100 μm and a cavity length of 5100 μm. Both cavity mirrors had an AR coating ($R \leqslant 5\%$), and the cleaved faces of the crystal were mechanically matted to prevent quenching of lasing. The laser crystals were mounted on copper heat sinks so as to ensure unimpeded input and output of radiation from both sides. Application of AR-coatings on both cavity mirrors was used to suppress rereflections of probe radiation, as well as to maximise the input and output of probe radiation into the waveguide of the sample under study.

The lasing wavelength of the samples was equal to 1030 nm. The probe radiation wavelength was chosen so that amplification and self-absorption were absent in the active region and in the layers of the laser heterostructure. The electroluminescence spectra of the lasers based on the heterostructures under study at high pump currents are given in [1]; the long-wavelength edge of their spontaneous emission corresponds to a wavelength of 1075 nm. Therefore, as a source of probe radiation we selected a semiconductor laser with a wavelength of 1100 nm and a waveguide thickness of 1.7 μm. These lasers were fabricated using a standard procedure and had an aperture of 100 μm, a cavity of length 2 to 4 mm and rear highly reflecting and front AR-coated mirrors.

4. Experimental

In the experiment, the probe laser operated in cw mode, and the semiconductor laser under study was pumped by current pulses with a duration of 100 ± 10 ns and an amplitude of 5 – 100 A. Both lasers were thermally stabilised.

Radiation of the probe laser was first coupled into the active part of the studied laser, which was formed under a stripe contact, and then into the lateral passive part, which was not pumped by the current pulses. The CCD-camera made it possible to control the input of radiation into a selected part of the laser crystal. The monochromator provided a transmission of the wavelengths in the 1100 ± 5 nm region, enabling the selection of probe radiation with allowance for the width of its spectrum (6 nm).

Figure 2 shows typical photoresponses of probe radiation coupled into the active part of the test sample at different amplitudes of the pump current. The shape of the dip in the photoresponse of probe radiation corresponds to the shape of the pump current pulse, and the amplitude of the dip increases with its growth.

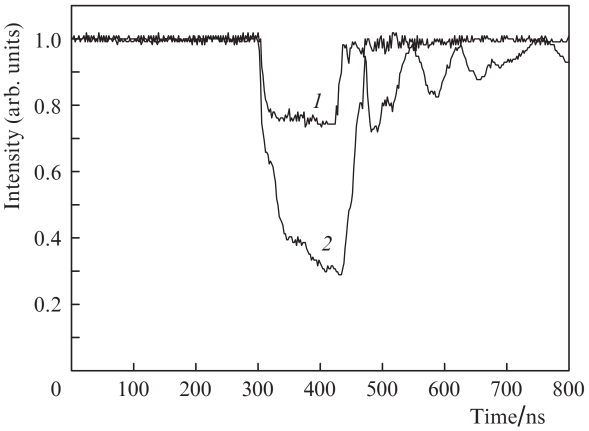

Figure 2. Photoresponses of probe radiation coupled into the active part of the laser crystal under study at pulsed pump currents of (*1*) 5 A (1 kA cm^{-2}) and (*2*) 100 A (20 kA cm^{-2}).

In photoresponses of probe radiation coupled into the passive part of the crystal, there was a dip, the depth of which was independent of the pump current. In our opinion, the thus registered signal can be caused by a spread of the current into the passive region and a partial passage of probe radiation in the active region of the laser crystal.

The data obtained allow us to assert with sufficient accuracy that pulsed pumping of the test sample leads to an increase in the absorption coefficient of probe radiation. Using formula (2) we calculated the change in the absorption coefficient for the pump current amplitudes of 5 to 100 A (from 1 to 20 kA cm^{-2}), the results of which are shown in Fig. 3. As follows from Fig. 3, for all of the samples the dependence of the absorption coefficient on the pump current does not tend to zero at a zero current amplitude.

To clarify the reasons for this fact, we performed an experiment in which the lasers in question were pumped by current pulses with a duration of 1 ± 0.1 μs and an amplitude of 0.3 to 10 A (from 0.06 to 2 kA cm^{-2}). This regime of pulsed

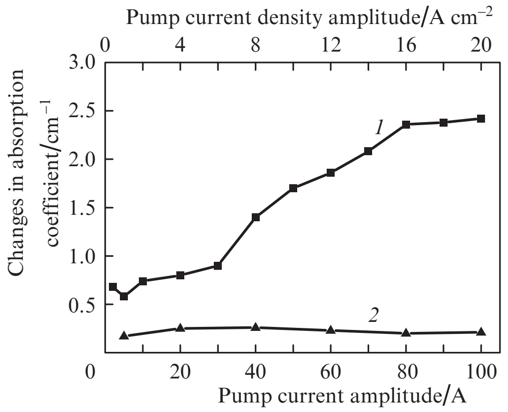

Figure 3. Typical dependences of changes in the absorption coefficient of probe radiation on the pump current in the (*1*) active and (*2*) passive parts of the sample.

current pumping allowed us to investigate in detail the behaviour of the absorption coefficient at low amplitudes of the pump current. Figure 4 shows the results of studying the changes in the absorption coefficient at low amplitudes of the pump current, which at low levels of pulsed current pumping actually tends to zero. It is important to note that this dependence has a sharp kink at a current corresponding to the threshold current of the studied laser, which is about 2 A (0.4 kA cm^{-2}).

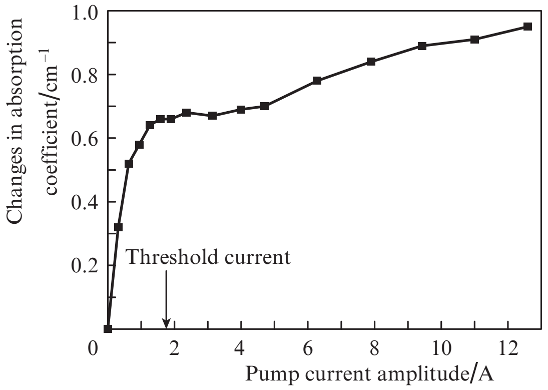

Figure 4. Typical dependence of changes in the absorption coefficient of probe radiation on the pump current in heterostructure layers of the test sample pumped by microsecond pulses.

5. Discussion of the results and conclusions

The proposed method for studying the absorption coefficient in layers of a laser heterostructure makes it possible to determine its growth under pulsed current pumping. We have found that in the layers of a semiconductor laser heterostructure, probe radiation experiences absorption with increasing level of pulsed current pumping. An increase in absorption in the unpumped part of the crystal is negligible and is probably due to current spreading and partial propagation of probe radiation in the pumped region. A sharp increase in the absorption coefficient at a pump current less than 2 A (0.4 kA cm^{-2}) (Fig. 4) is likely associated with an increase in charge carrier concentration in the quantum wells of the active region. After reaching the lasing threshold the concentration of charge carriers in the quantum wells remains virtually the same, and an increase in free-carrier absorption slows down. A further, almost linear, increase in the absorption coefficient corresponds in magnitude and behaviour to the growth of the internal optical loss with increasing pump current density, which was reported in our papers [1, 2].

Application of this method of research has revealed that an increase in free-carrier absorption in layers of a laser heterostructure with increasing level of current pumping can be one of the most likely mechanisms of the growth of the internal optical loss. The proposed method makes it possible, in particular, to determine the absorption coefficient by free charge carriers in quantum wells at different pump currents near the lasing threshold, which can be useful in the study of lasers based on heterostructures of different types.

Our further studies will be aimed at improving the presented method and at investigating the absorption coefficient in heterostructures of various types, as well as at studying the absorption coefficient upon variation of the semiconductor laser temperature.

Acknowledgements. This work was performed under the State Task of the Ioffe Institute.

References

1. Veselov D.A., Kapitonov V.A., Pikhtin N.A., Lyutetskiy A.V., Nikolaev D.N., Slipchenko S.O., Sokolova Z.N., Shamakhov V.V., Shashkin I.S., Tarasov I.S. *Kvantovaya Elektron.*, **44** (11), 993 (2014) [*Quantum Electron.*, **44** (11), 993 (2014)].
2. Veselov D.A., Pikhtin N.A., Lyutetskiy A.V., Nikolaev D.N., Slipchenko S.O., Sokolova Z.N., Shamakhov V.V., Shashkin I.S., Kapitonov V.A., Tarasov I.S. *Kvantovaya Elektron.*, **45** (7), 597 (2015) [*Quantum Electron.*, **45** (7), 597 (2015)].
3. Bezotosnyi V.V., Bondarev V.Yu., Krokhin O.N., Oleshchenko V.A., Pevtsov V.F., Popov Yu.M., Cheshev E.A. *Fiz. Tekh. Poluprovodn.*, **48** (1), 114 (2014).
4. Sokolova Z.N., Tarasov I.S., Asryan L.V. *Fiz. Tekh. Poluprovodn.*, **45** (11), 1553 (2011).
5. Wang X., Crump P., Wenzel H., Liero A., Hoffmann T., Pietrzak A., Schultz C.M., Klehr A., Ginolas A., Einfeldt S., Bugge F., Erbert G., Tränkle G. *IEEE J. Quantum Electron.*, **46** (5), 658 (2010).
6. Miftakhutdinov D.R., Akimova I.V., Bogatov A.P., Gushchik T.I., Drakin A.E., D'yachkov N.V., Popovich V.V., Nekrasov A.P. *Kvantovaya Elektron.*, **38** (11), 993 (2008) [*Quantum Electron.*, **38** (11), 993 (2008)].
7. Ryvkin B.S., Avrutin E.A. *Electron. Lett.*, **42** (22), 1283 (2006).
8. Sokolova Z.N., Tarasov I.S., Asryan L.V. *Fiz. Tekh. Poluprovodn.*, **46** (8), 1067 (2012).
9. Asryan L.V., Sokolova Z.N. *J. Appl. Phys.*, **115**, 023107 (2014).
10. Pikhtin N.A., Slipchenko S.O., Sokolova Z.N., Tarasov I.S. *Fiz. Tekh. Poluprovodn.*, **38** (3), 374 (2004).